On the Relaying Protocols Without Causing Capacity Loss at a Primary Node in Cognitive Radio Networks

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***Abstract*—This paper raises the question of whether the secondary user can attain a nonzero achievable rate without causing capacity loss at the primary user, even when it is utilizing the channel in cognitive radio networks (CRNs). It is assumed that secondary nodes are aware of the channel state information (CSI) of primary nodes and of how the primary nodes operate, whereas the primary nodes operate with no prior knowledge about the secondary nodes. We first propose a *full-duplex* relaying protocol for the cognitive radio (CR) network with a single relay node shared by both the primary and the secondary networks. In this case, the shared relay is assumed to have full CSI of the primary nodes and to know how the primary and secondary nodes operate. The proposed relaying protocol enables the secondary network to achieve nonzero rates without causing capacity loss at the primary network in a *certain* channel condition. Then, we also propose three *half-duplex* relaying protocols for the CR network with two relays, each of which is dedicated to the primary or the secondary network, respectively. It is shown that appropriate combinations of the proposed three half-duplex relaying protocols make it *always* possible for the secondary network to achieve nonzero rates without causing capacity loss at the primary network. Achievable rates of the proposed full- and half-duplex relaying protocols are evaluated through extensive computer simulations. Simulation results show that the proposed relaying protocols provide nonzero achievable rates of the secondary network over a wide range of signal-to-noise ratios (SNRs).**

***Index Terms*—Cognitive radio networks (CRNs), dirty-paper coding (DPC), full-duplex relay, half-duplex relay, power control, spectrum sharing.**

I. Introduction

COGNITIVE radios (CRs) have drawn a great deal of interest in academic, industrial, and regulation communities as one of a few promising technologies to resolve the scarcity of available wireless spectrum bands [1]–[4]. CRs improve spectral utilization by allowing unlicensed secondary users to access licensed primary users' spectrum bands. Various access techniques in CR systems have been introduced, and some of the most recent results can be found in special issues [5]–[9].

There exist, in general, two types of methods known in literature for the CRs to accommodate the access of the secondary users. One allows the secondary users to access the licensed spectrum bands only if they are not used by the primary users. This type of access technology is referred to as spectrum overlay or opportunistic spectrum access [2]. On the other hand, spectrum underlay or spectrum sharing allows the secondary users to access the licensed spectrum bands even though they are used by the primary users. One well-known spectrum underlay method allows the secondary users only if interference from the secondary senders to the primary receivers is maintained below a certain threshold, called the *interference temperature* [10]–[19].

Since the secondary user is allowed only through the spectrum bands that are not used by the primary user in the spectrum overlay methods, there is no loss at the primary user's achievable rate, whereas the secondary user's achievable rate is likely to be poor if the primary user occupies the spectrum with high probability. On the other hand, the primary user's achievable rate is deteriorated when the secondary user is allowed in the spectrum underlay methods, although the secondary user's achievable rate is improved. To maintain the primary user's achievable rate even when the secondary user is allowed to access the same spectrum bands, it is proposed to opportunistically permit excessive interference at the primary receiver by performing opportunistic multiuser decoding [20]. This scheme, however, can only be applied to the uplink of cellular-like systems where the primary receiver is aware of the channel state information (CSI) of secondary users and of how the secondary sender operates in practice. Furthermore, a similar approach not causing capacity loss at the primary network was proposed for intersymbol interference channels, but the proposed scheme can be applied only when a certain condition on the delay profiles of wireless channel is satisfied [21].

CR networks (CRNs) have recently been investigated in the literature to improve throughput or outage performance of the secondary network. In [22], the outage probability of the CRN with cooperation between secondary users in spectrum underlay method is evaluated. In [23], the problem of resource allocation in the CRN for improving the throughput is investigated, and the proportional fair scheduling, the fluctuations of usable spectrum resource, and the channel quality variations over the frequency domain are taken into account. In [24], the utilization of cooperative relay nodes to assist the transmission and improvement spectrum efficiency of the CRN is investigated. In particular, they considered the relay selection

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and spectrum allocation problem and implemented the testbed based on the Universal Software Radio Peripheral. In [25], two-hop relaying protocols, which preserve the *outage performance* of a primary node, are proposed, but the proposed protocols do not guarantee the performance of the primary node in terms of capacity. In short, relay nodes have been utilized to improve throughput or outage performance in CRNs operating in either underlay or overlay mode, but the capacity loss still exists at the primary network when the relay nodes are adopted in the underlay mode.

In this paper, we propose a *novel* relaying technique for CRNs that allows the secondary user to access the spectrum bands that are being used by the primary user and still not to cause any capacity loss at the primary user. In general, the secondary user does not transmit if the primary user is sending its data in the overlay mode, and the data transmission of the secondary user results in capacity loss at the primary user due to the interference from the secondary user, although the interference is maintained below a predetermined threshold (i.e., interference temperature). We first consider two-hop relaying CR communications with a single full-duplex relay shared by both the primary and the secondary networks. By exploiting a unique property of the primary channel capacity, it is shown that the secondary network can obtain a nonzero achievable rate in this scenario if the signal-to-noise ratio (SNR) of the primary user at the shared relay node is smaller than the SNR of the relay signal at the primary receiver. Then, we consider two-hop half-duplex relaying CR communications with two relays, each of which is dedicated to the primary and secondary networks, respectively. We show that the secondary sender can *always* obtain a nonzero achievable rate in this scenario. To the best of our knowledge, there has been no such attempt as nonzero rates are achieved in the CRN, while not causing any loss in terms of the *average* primary channel capacity. We obtain average achievable rates of the proposed relaying protocols through computer simulations.

The rest of this paper is organized as follows. In Section II, we propose a full-duplex two-hop relaying protocol with a single relay. In Section III, we also propose three half-duplex two-hop relaying protocols with one primary relay and one secondary relay according to different channel conditions. Note that we clearly introduce two different system models in Sections II and III, respectively. In Section IV, average achievable rates of the proposed two-hop relaying protocols are shown through computer simulations and compared with each other. Finally, Section V presents the conclusion.

II. FULL-DUPLEX RELAYING PROTOCOL WITH A SINGLE RELAY

Here, we consider full-duplex relaying CR communications with a single shared relay that is aware of the primary and secondary relay channels and of how the primary and secondary senders and receivers operate. In this paper, we assume that the *self-interference* induced by the full-duplex relay's own transmission is perfectly removed by the help of recent technical progresses in literature, including [26]–[28].

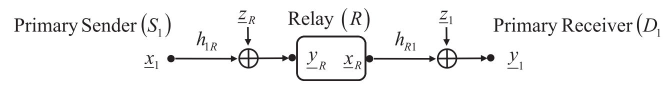

Fig. 1. Gaussian two-hop relay channel with the primary sender and receiver.

Recently, a similar network model has been investigated in both the CRNs [29] and the interference networks [30], [31]. In [29], the optimal power allocation at the secondary sender and the relay with the amplify-and-forward technique are considered, but it is assumed that the network operates with the underlay mode and that the relay operates with the half-duplex. In [30] and [31], the two-user Gaussian interference channel with a shared CR is considered, and the achievable rate region is obtained, but it is required that two transmitters and the shared relay collaborate for optimizing the sum-rate performance of the network, whereas the secondary user and the shared relay collaborate for both protecting the primary network and maximizing throughput of the secondary network in this paper. In other words, the primary network does not consider the secondary network, including the shared relay in this paper.

Assuming that the primary sender and receiver do not have any prior knowledge on the secondary sender and receiver, whereas the secondary sender and receiver are aware of the primary relay channel and of how the primary sender and receiver as well as the relay operate, we show that it is possible for the secondary sender to transmit data, even without causing a loss at the primary channel capacity.[1] As shown in the succeeding discussion, it results from a unique property of the primary channel capacity and by the help of the relay for the secondary sender and receiver.

We first consider the primary relay channel given by a Gaussian two-hop relay channel,[2] as shown in Fig. 1, where the primary sender $\mathcal{S}_1$ and the relay $\mathcal{R}$ transmit codewords $\underline{x}_1 = (x_{11}, \ldots, x_{1n})$ and $\underline{x}_R = (x_{R1}, \ldots, x_{Rn})$ with powers P_1 and P_R, respectively. Assuming that the relay $\mathcal{R}$ operates in a full-duplex manner such that it transmits and receives at the same time, the signals received by the relay $\mathcal{R}$ and the primary receiver $\mathcal{D}_1$ are given by

$$\underline{y}_R = h_{1R}\underline{x}_1 + \underline{z}_R \tag{1}$$

$$\underline{y}_1 = h_{R1}\underline{x}_R + \underline{z}_1 \tag{2}$$

respectively, where h_{1R} and h_{R1} are constants, and $\underline{z}_R$ and $\underline{z}_1$ are noise vectors consisting of n zero-mean independently and

[1] The assumption has been widely adopted in studies on cognitive (relay) networks where the cognitive network (the secondary sender, CR, and secondary receiver) knows the channel coefficients of the primary network and how the primary network operates [20]–[22], [32]. We follow the convention since we focus on the theoretical aspect of CRNs in this paper.

[2] In this paper, the primary sender is assumed to be located so far away from the primary receiver that there is no direct communication path between them. Hence, the relay is placed to make a possible communication path between them, and this relay channel model is usually called the two-hop relay channel. Moreover, the primary sender and receiver are licensed nodes and operate with no awareness of the secondary nodes.

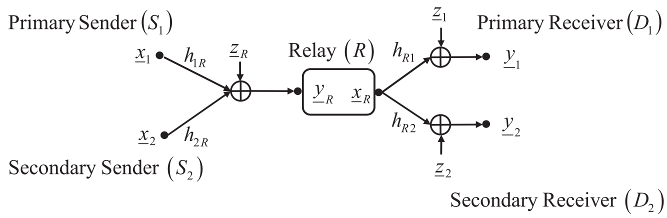

Fig. 2. Gaussian two-hop relay channel with both the primary and the secondary senders and receivers.

identically distributed (i.i.d.) Gaussian random variables with variances N_R and N_1, respectively. To simplify notations, we define $g_{1R} \triangleq |h_{1R}|^2$ and $g_{R1} \triangleq |h_{R1}|^2$.

The following theorem shows the capacity of the Gaussian two-hop relay channel.

Lemma 1: The capacity of the Gaussian two-hop relay channel is given by[3]

$$C_1 = \min\left\{C\left(\frac{g_{1R}P_1}{N_R}\right), C\left(\frac{g_{R1}P_R}{N_1}\right)\right\} \quad \text{[bits/channel use]} \tag{3}$$

where $C(x) \triangleq (1/2)\log_2(1+x)$.

Proof: The achievability is proved by the decode-and-forward relaying scheme, and the converse is proved by the max-flow min-cut theorem [33]. ■

We now consider both the primary and the secondary relay channels together, as shown in Fig. 2, where the secondary sender $\mathcal{S}_2$ transmits a codeword $\underline{x}_2 = (x_{21}, \ldots, x_{2n})$ with power P_2, and the received signals at the relay $\mathcal{R}$ and the secondary receiver $\mathcal{D}_2$ are given by

$$\underline{y}_R = h_{1R}\underline{x}_1 + h_{2R}\underline{x}_2 + \underline{z}_R \tag{4}$$

$$\underline{y}_2 = h_{R2}\underline{x}_R + \underline{z}_2 \tag{5}$$

respectively. It is notable that the received signal at $\mathcal{D}_1$, i.e., $\underline{y}_1$, is still the same as (2), whereas $\underline{y}_R$ is slightly modified from (1), so that it also includes the signal received from $\mathcal{S}_2$. Similarly, h_{2R} and h_{R2} are constants, $\underline{z}_2$ is a noise vector consisting of n zero-mean i.i.d. Gaussian random variable with a variance N_2, and we define $g_{2R} \triangleq |h_{2R}|^2$ and $g_{R2} \triangleq |h_{R2}|^2$. It is said that the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ and the relay $\mathcal{R}$ are *cognitive* in a sense that they know the existence of each other and have prior knowledge on both the primary and the secondary relay channels, as well as their codebooks [29]–[31].

Since the relay $\mathcal{R}$ has both the primary and the secondary codebooks, the channel from $(\mathcal{S}_1, \mathcal{S}_2)$ to $\mathcal{R}$ can be seen as a multiple-access channel (MAC), and the channel from $\mathcal{R}$ to $(\mathcal{D}_1, \mathcal{D}_2)$ can be seen as a broadcast channel (BC) [33]. Given the primary data rate as its channel capacity C_1 in (3), we determine the secondary data rate so that $\mathcal{S}_2$ delivers data to $\mathcal{D}_2$ without causing a loss at the primary channel capacity. Therefore, it is possible for $\mathcal{S}_2$ to transmit data only when C_1

[3]In this paper, the transmission rates such as channel capacities or achievable rates are quantified in bits/channel use.

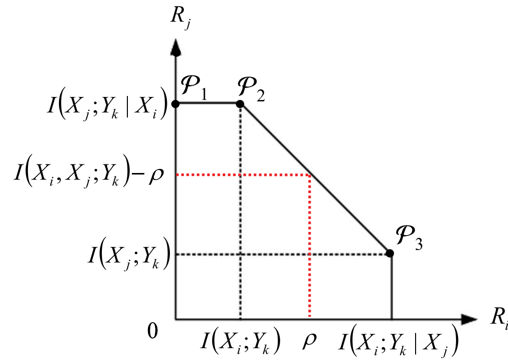

Fig. 3. Capacity region of the MAC from (i, j) to k.

lies inside the capacity region of the MAC from $(\mathcal{S}_1, \mathcal{S}_2)$ to $\mathcal{R}$, as shown in Fig. 3, i.e., [33]

$$C_1 \leq I(X_1; Y_R|X_2) = C\left(\frac{g_{1R}P_1}{N_R}\right) \tag{6}$$

$$R_2 \leq I(X_2; Y_R|X_1) = C\left(\frac{g_{2R}P_2}{N_R}\right) \tag{7}$$

$$C_1 + R_2 \leq I(X_1, X_2; Y_R) = C\left(\frac{g_{1R}P_1 + g_{2R}P_2}{N_R}\right) \tag{8}$$

where (6) is always satisfied from (3).

On the other hand, since $\mathcal{D}_1$ has no prior knowledge on the secondary codebook, the transmitted signals at $\mathcal{R}$ for $\mathcal{D}_2$ are simply considered as interference at $\mathcal{D}_1$. If $\mathcal{R}$ transmits the primary data with power of αP_R together with the secondary data with power of $(1-\alpha)P_R$ after superimposing them as a form of a superposition code,[4] then for reliable decoding of the primary signals at $\mathcal{D}_1$, it is required to satisfy

$$C_1 \leq C\left(\frac{g_{R1}\alpha P_R}{N_1 + g_{R1}(1-\alpha)P_R}\right) \tag{9}$$

where $\alpha \in [0,1]$. Note that from (3), if $g_{1R}P_1/N_R > g_{R1}P_R/N_1$, then $C_1 = C(g_{R1}P_R/N_1)$, and hence, $\alpha = 1$ is the only choice to satisfy (9), i.e., $\mathcal{R}$ cannot transmit any information for the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$. Therefore, $\mathcal{R}$ can send the secondary data only if $g_{1R}P_1/N_R \leq g_{R1}P_R/N_1$.

Considering the MAC from $(\mathcal{S}_1, \mathcal{S}_2)$ to $\mathcal{R}$ and the BC from $\mathcal{R}$ to $(\mathcal{D}_1, \mathcal{D}_2)$ together, the following two conditions should be satisfied if $\mathcal{S}_2$ can send any information to $\mathcal{D}_2$.

i) Since $\mathcal{R}$ can send the secondary data only if $g_{1R}P_1/N_R \leq g_{R1}P_R/N_1$, C_1 should be given by $C(g_{1R}P_1/N_R)$.
ii) Since $C_1 = C(g_{1R}P_1/N_R)$ should lie inside the capacity region of the MAC from $(\mathcal{S}_1, \mathcal{S}_2)$ to $\mathcal{R}$, from (8), we have

$$R_2 \leq C\left(\frac{g_{1R}P_1 + g_{2R}P_2}{N_R}\right) - C_1 = C\left(\frac{g_{2R}P_2}{N_R + g_{1R}P_1}\right) \tag{10}$$

which implies (7).

As a result, we have the following theorem for the achievable rate of the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$.

[4]The superposition coding is a well-known information-theoretic coding technique that was originally proposed in [34] to show that it is optimal for the degraded BCs. For more detailed information, see [33, Sec. 15.6] and [34].

Theorem 1: If the primary channel is given by the Gaussian two-hop relay channel satisfying $g_{1R}P_1/N_R \le g_{R1}P_R/N_1$, then an achievable rate for the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ is given by

$$C_2^- = \min\left\{C\left(\frac{g_{2R}P_2}{N_R + g_{1R}P_1}\right), C\left(\frac{g_{R2}(1-\alpha^*)P_R}{N_2}\right)\right\} \tag{11}$$

where

$$\alpha^* = \frac{g_{1R}(N_1 + g_{R1}P_R)P_1}{g_{R1}(N_R + g_{1R}P_1)P_R}. \tag{12}$$

Proof: We propose a decode-and-forward relaying scheme as follows.

Primary sender $\mathcal{S}_1$: For a message $w_1 \in \{1, \ldots, 2^{nC_1}\}$, the primary sender $\mathcal{S}_1$ transmits a codeword $\underline{x}_1(w_1)$ that is chosen from a Gaussian codebook with its distribution of $\mathcal{N}(0, P_1)$.

Secondary sender $\mathcal{S}_2$: For a message $w_2 \in \{1, \ldots, 2^{nR_2}\}$, the secondary sender $\mathcal{S}_2$ transmits a codeword $\underline{x}_2(w_2)$ that is chosen from a Gaussian codebook with its distribution of $\mathcal{N}(0, P_2)$.

Relay $\mathcal{R}$: The relay $\mathcal{R}$ jointly decodes both $\underline{x}_1(w_1)$ and $\underline{x}_2(w_2)$ with a joint typicality decoder. The probability of error would be arbitrarily small as long as (10) is satisfied. The relay $\mathcal{R}$ chooses a codeword $\underline{x}_{R1}(w_1)$ from a Gaussian codebook with its distribution of $\mathcal{N}(0, \alpha P_R)$. Then, the relay applies the dirty-paper coding (DPC) [35] regarding $\underline{x}_{R1}(w_1)$ as a noncausally known interference for the intended receiver $\mathcal{D}_2$. This can be done by constructing an auxiliary sequence $\underline{u}(w_2)$ for the bin index of w_2 following the distribution given by

$$U = \sqrt{g_{R2}}X_{R2} + \beta\sqrt{g_{R2}}X_{R1} \tag{13}$$

where $X_{R2} \sim \mathcal{N}(0, (1-\alpha)P_R)$, $X_{R1} \sim \mathcal{N}(0, \alpha P_R)$, and

$$\beta = \frac{g_{R2}(1-\alpha)P_R}{g_{R2}(1-\alpha)P_R + N_2}. \tag{14}$$

After the relay $\mathcal{R}$ chooses $\underline{x}_{R2}(w_2)$ that is jointly typical with $(\underline{x}_{R1}(w_1), \underline{u}(w_2))$, it transmits $\underline{x}_R = \underline{x}_{R1}(w_1) + \underline{x}_{R2}(w_2)$.

Primary receiver $\mathcal{D}_1$: The primary receiver $\mathcal{D}_1$ decodes $\underline{x}_{R1}(w_1)$ simply considering $\underline{x}_{R2}(w_2)$ as interference. The probability of error would be arbitrarily small as long as (9) is satisfied.

Secondary receiver $\mathcal{D}_2$: The secondary receiver $\mathcal{D}_2$ decodes $\underline{u}(w_2)$. By the DPC with β satisfying (14), the probability of error would be arbitrarily small as long as

$$R_2 \le C\left(\frac{g_{R2}(1-\alpha)P_R}{N_2}\right). \tag{15}$$

By the definition of $C_2^- \triangleq \max R_2$ and from (9), (10), and (15), we have

$$C_2^- = \max_{\alpha}\min\left\{C\left(\frac{g_{2R}P_2}{N_R + g_{1R}P_1}\right), C\left(\frac{g_{R2}(1-\alpha)P_R}{N_2}\right)\right\} \tag{16a}$$

$$\text{subject to (9).} \tag{16b}$$

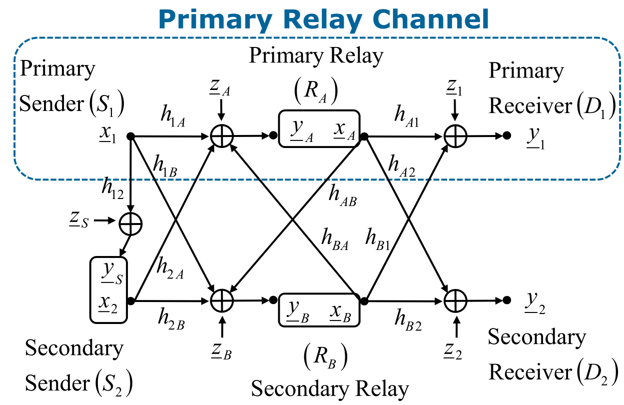

Fig. 4. Gaussian two-hop half-duplex relay channel with one primary relay and one secondary relay.

Since C_2^- is a nonincreasing function of α, the optimal α^* is chosen to satisfy

$$C_1 = C\left(\frac{g_{R1}\alpha P_R}{N_1 + g_{R1}(1-\alpha)P_R}\right). \tag{17}$$

■

Note that the secondary data rate C_2^- in (11) is actually achieved even though the primary pair $(\mathcal{S}_1, \mathcal{D}_1)$ does not have any prior knowledge on the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$, and as a result, $\mathcal{D}_1$ simply considers the signal transmitted at $\mathcal{R}$ for $\mathcal{D}_2$, i.e., $\underline{x}_{R2}(w_2)$, as interference.

III. Half-Duplex Relaying Protocols With Two Relays

Here, we consider two-hop half-duplex relaying CR communications with one primary relay and one secondary relay, as shown in Fig. 4, where the two relays are operating in a half-duplex manner such that they cannot transmit and receive at the same time. We assume that the primary sender, relay, and receiver are only aware of the primary relay channel and of how they themselves operate each other, whereas the secondary sender, relay, and receiver are aware of both the primary and the secondary relay channels and of how they themselves operate each other, as well as of how the primary sender, relay, and receiver operate each other. By exploiting a unique property of the half-duplex relaying, we show that it is *always* possible for the secondary sender to deliver data to its receiver, even without causing any loss at the primary channel capacity.

We first consider the primary relay channel given by a Gaussian two-hop half-duplex relay channel, as shown in Fig. 4, where the primary relay $\mathcal{R}_A$ operates in a half-duplex manner such that receiving and transmitting periods at $\mathcal{R}_A$ are the same and repeated alternately. During the first period of $n/2$ symbols, the primary sender $\mathcal{S}_1$ transmits data and $\mathcal{R}_A$ receives them while the primary receiver $\mathcal{D}_1$ is inactive. During the second period of $n/2$ symbols, $\mathcal{R}_A$ transmits data and $\mathcal{D}_1$ receives them while $\mathcal{S}_1$ is inactive. Then, these two operating phases are repeated alternately. We assume that $\mathcal{S}_1$ and $\mathcal{R}_A$ transmit codewords $\underline{x}_1 = (x_{11}, \ldots, x_{1n/2})$ and $\underline{x}_A = (x_{A1}, \ldots, x_{An/2})$

with powers P_1 and P_A, respectively. The received signals at $\mathcal{R}_A$ and $\mathcal{D}_1$ are then given by

$$\underline{y}_A = h_{1A}\underline{x}_1 + \underline{z}_A \tag{18}$$

$$\underline{y}_1 = h_{A1}\underline{x}_A + \underline{z}_1 \tag{19}$$

respectively, where h_{1A} and h_{A1} are constants, and $\underline{z}_A$ and $\underline{z}_1$ are noise vectors consisting of n zero-mean i.i.d. Gaussian random variables with variances N_A and N_1, respectively. To simplify notations, we define $g_{1A} \triangleq |h_{1A}|^2$ and $g_{A1} \triangleq |h_{A1}|^2$. The capacity of the primary Gaussian two-hop half-duplex relay channel can be easily obtained from (3) and is given by

$$C_1 = \frac{1}{2}\min\left\{C\left(\frac{g_{1A}P_1}{N_A}\right), C\left(\frac{g_{A1}P_A}{N_1}\right)\right\} \tag{20}$$

where it is notable that (20) is half of (3) since $\mathcal{S}_1$ and $\mathcal{D}_1$ are active only for half of the entire time periods.

We now consider both the primary and the secondary relay channels together, as shown in Fig. 4, where the secondary relay $\mathcal{R}_B$ also operates in a half-duplex manner. The secondary sender $\mathcal{S}_2$ and $\mathcal{R}_B$ transmit codewords $\underline{x}_2$ and $\underline{x}_B$ with powers P_1 and P_B, respectively. Interestingly, we assume that $\mathcal{S}_2$ may receive signals from $\mathcal{S}_1$. The received signals at $\mathcal{S}_2$, $\mathcal{R}_A$, $\mathcal{R}_B$, $\mathcal{D}_1$, and $\mathcal{D}_2$ are then changed according to which half-duplex relaying protocol is used, as explained later. The received signals from all possible incoming paths at $\mathcal{S}_2$, $\mathcal{R}_A$, $\mathcal{R}_B$, $\mathcal{D}_1$, and $\mathcal{D}_2$ are given by

$$\underline{y}_S = h_{12}\underline{x}_1 + \underline{z}_S \tag{21}$$

$$\underline{y}_A = h_{1A}\underline{x}_1 + h_{2A}\underline{x}_2 + h_{BA}\underline{x}_B + \underline{z}_A \tag{22}$$

$$\underline{y}_B = h_{1B}\underline{x}_1 + h_{2B}\underline{x}_2 + h_{AB}\underline{x}_A + \underline{z}_B \tag{23}$$

$$\underline{y}_1 = h_{A1}\underline{x}_A + h_{B1}\underline{x}_B + \underline{z}_1 \tag{24}$$

$$\underline{y}_2 = h_{A2}\underline{x}_A + h_{B2}\underline{x}_B + \underline{z}_2 \tag{25}$$

respectively, where h_{12}, h_{2A}, h_{BA}, h_{1B}, h_{2B}, h_{AB}, h_{B1}, h_{A2}, and h_{B2} are constants; $\underline{z}_S$ and $\underline{z}_2$ are noise vectors consisting of n zero-mean i.i.d. Gaussian random variables with variances N_S and N_2, respectively; and we define $g_{12} \triangleq |h_{12}|^2$, $g_{2A} \triangleq |h_{2A}|^2$, $g_{BA} \triangleq |h_{BA}|^2$, $g_{1B} \triangleq |h_{1B}|^2$, $g_{2B} \triangleq |h_{2B}|^2$, $g_{AB} \triangleq |h_{AB}|^2$, $g_{B1} \triangleq |h_{B1}|^2$, $g_{A2} \triangleq |h_{A2}|^2$, and $g_{B2} \triangleq |h_{B2}|^2$. The secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ and the secondary relay $\mathcal{R}_B$ are said to be *cognitive* in a sense that they know the existence of each other and have prior knowledge on both the primary and the secondary relay channels, as well as their codebooks.

Since both $\mathcal{R}_A$ and $\mathcal{D}_1$ do not have the secondary codebook, the received signals from $\mathcal{S}_2$ and $\mathcal{R}_B$ are simply considered as interference at $\mathcal{R}_A$ and $\mathcal{D}_1$. On the other hand, since $\mathcal{S}_2$, $\mathcal{R}_B$, and $\mathcal{D}_2$ have both the primary and the secondary codebooks, the channel from $(\mathcal{S}_1, \mathcal{S}_2, \mathcal{R}_A)$ to $\mathcal{R}_B$ and the channel from $(\mathcal{R}_A, \mathcal{R}_B)$ to $\mathcal{D}_2$ sometimes can be seen as MACs, and the channel from $\mathcal{S}_2$ to $(\mathcal{R}_A, \mathcal{R}_B)$ and the channel from $\mathcal{R}_B$ to $(\mathcal{R}_A, \mathcal{D}_1, \mathcal{D}_2)$ can sometimes be seen as BCs. Given the primary data rate as its channel capacity C_1 in (20), we determine the secondary rate so that $\mathcal{S}_2$ delivers data to $\mathcal{D}_2$ without causing any loss at the primary channel capacity. To make it *always* possible for $\mathcal{S}_2$ to deliver data to $\mathcal{D}_2$, we propose three half-duplex relaying protocols, such as Protocols I and II, when $C_1 = (1/2)$ $C(g_{A1}P_A/N_1)$, equivalently $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, and Protocol III when $C_1 = (1/2)C(g_{1A}P_1/N_A)$, equivalently $g_{1A}P_1/N_A \leq g_{A1}P_A/N_1$. When $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, we then choose the best between Protocols I and II to yield a larger achievable rate according to the channel parameters.

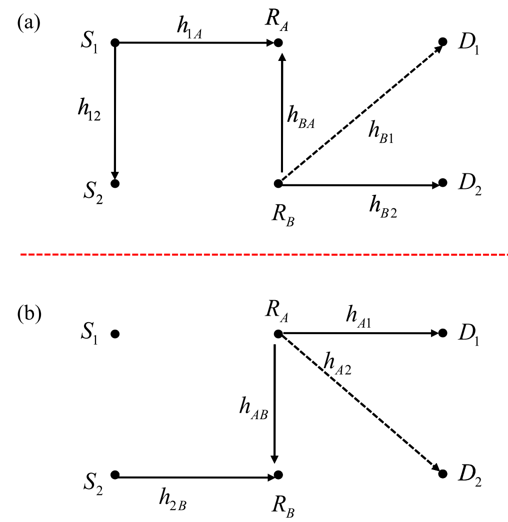

Fig. 5. Protocol I. (a) Phase I. (b) Phase II.

A. Protocol I

For the case of $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, we first propose Protocol I, which is defined by a two-phase relaying scheme, as shown in Fig. 5, where Phases I and II are repeated alternately. In Phase I, $\mathcal{S}_1$ and $\mathcal{R}_B$ transmit while $\mathcal{S}_2$, R_A, and $\mathcal{D}_2$ receive. In Phase II, $\mathcal{S}_2$ and $\mathcal{R}_A$ transmit while $\mathcal{R}_B$ and $\mathcal{D}_1$ receive. Note that $\mathcal{D}_1$ ($\mathcal{D}_2$) is inactive in Phase I (II), respectively. In Protocol I, $\mathcal{R}_B$ obtains the secondary data by decoding the received signals from $\mathcal{S}_2$ in Phase II, and $\mathcal{R}_B$ then retransmits them to $\mathcal{D}_2$ in Phase I. We propose two different schemes according to how $\mathcal{R}_B$ obtains the secondary data in Phase II.

1) Case of $g_{12}/N_S \geq g_{1A}/N_A$: Since the primary data rate C_1 is less than or equal to the channel capacity of the channel from $\mathcal{S}_1$ to $\mathcal{S}_2$, i.e., $C_1 = (1/2)C(g_{1A}P_1/N_A) \leq (1/2)C(g_{12}P_1/N_S)$, $\mathcal{S}_2$ can reliably decode the received signals from $\mathcal{S}_1$ in Phase I. This makes it possible for $\mathcal{S}_2$ to know which signals would be transmitted from $\mathcal{R}_A$ to $\mathcal{R}_B$ in Phase II. Hence, $\mathcal{S}_2$ can employ the DPC for the intended receiver $\mathcal{R}_B$ regarding the received signals from $\mathcal{R}_A$ as noncausally known interference [35]. Then, $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_2$ in Phase II if

$$R_2 \leq \frac{1}{2}C\left(\frac{g_{2B}P_2}{N_B}\right) \tag{26}$$

where the effect of the interference caused by $\mathcal{R}_A$ is completely removed by the DPC [35].

2) Case of $g_{12}/N_S < g_{1A}/N_A$: Since $\mathcal{S}_2$ cannot decode the received signals from $\mathcal{S}_1$ in Phase I, the DPC cannot be applied at $\mathcal{S}_1$. Instead, we consider the channel $(\mathcal{R}_A, \mathcal{S}_2)$ to $\mathcal{R}_B$ in Phase II as a MAC. If $C_1 \le (1/2)C(g_{AB}P_A/N_B)$, then C_1 is located inside the MAC capacity region, as shown in Fig. 3, i.e.,

$$2C_1 \le I(X_A; Y_B|X_2) = C\left(\frac{g_{AB}P_A}{N_B}\right) \tag{27}$$

$$2R_2 \le I(X_2; Y_B|X_A) = C\left(\frac{g_{2B}P_2}{N_B}\right) \tag{28}$$

$$2(C_1+R_2) \le I(X_A, X_2; Y_B) = C\left(\frac{g_{AB}P_A + g_{2B}P_2}{N_B}\right). \tag{29}$$

Hence, $\mathcal{R}_B$ can reliably decode the received signals from both $\mathcal{S}_2$ and $\mathcal{R}_A$ if

$$R_2 \le \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{2B}P_2+g_{AB}P_A}{N_B}\right) - 2C_1\right\}. \tag{30}$$

On the other hand, if $C_1 > (1/2)C(g_{AB}P_A/N_B)$, then C_1 is located outside the MAC capacity region, and $\mathcal{R}_B$ cannot decode the received signals from $\mathcal{R}_A$. Simply considering them as interference, $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_2$ if

$$R_2 \le \frac{1}{2}C\left(\frac{g_{2B}P_2}{N_B + g_{AB}P_A}\right). \tag{31}$$

After obtaining the secondary data in Phase II, $\mathcal{R}_B$ retransmits them to $\mathcal{D}_2$ in Phase I. Then, $\mathcal{D}_2$ can reliably decode the received signals from $\mathcal{R}_B$ in Phase I if

$$R_2 \le \frac{1}{2}C\left(\frac{g_{B2}P_B}{N_2}\right). \tag{32}$$

In addition, since the transmitted signals at $\mathcal{R}_B$ should not affect the fact that $\mathcal{R}_A$ reliably decodes the received signals from $\mathcal{S}_1$ in Phase I, it is required to satisfy

$$C_1 = \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1}\right) \le \frac{1}{2}C\left(\frac{g_{1A}P_1}{N_A + g_{BA}P_B}\right) \tag{33}$$

where the received signals from $\mathcal{R}_B$ are simply considered to be interference at $\mathcal{R}_A$.

Finally, we have the following theorem about the achievable rate of the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ provided by Protocol I.

Theorem 2: If the primary channel is given by the Gaussian two-hop half-duplex relay channel satisfying $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, then Protocol I provides the following achievable rates for the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$.

- If $g_{12}/N_S \ge g_{1A}/N_A$, then

$$C_2^- = \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\} \tag{34}$$

where

$$P_B^* = \min\left\{\frac{1}{g_{BA}}\left(\frac{g_{1A}P_1}{g_{A1}P_A}\cdot N_1 - N_A\right), P_B\right\}. \tag{35}$$

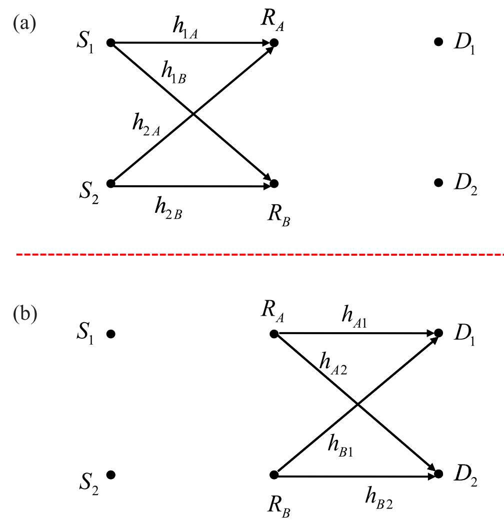

Fig. 6. Protocol II. (a) Phase I. (b) Phase II.

- If $g_{12}/N_S < g_{1A}/N_A$ and $C_1 \le (1/2)C(g_{AB}P_A/N_B)$, then

$$C_2^- = \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{2B}P_2 + g_{AB}P_A}{N_B}\right) - 2C_1 \; C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\}. \tag{36}$$

- If $g_{12}/N_S < g_{1A}/N_A$ and $C_1 > (1/2)C(g_{AB}P_A/N_B)$, then

$$C_2^- = \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B + g_{AB}P_A}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\}. \tag{37}$$

Proof: Equation (34) comes from (26) and (32). Equation (35) is chosen to maximize the right-hand-side (RHS) of (32) subject to (33). Equation (36) comes from (30) and (32). Equation (37) comes from (31) and (32). ∎

B. Protocol II

For the case of $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, we also propose Protocol II. It can, however, be used only when $C_1 \le (1/2)C(g_{1B}P_1/N_B)$. The reason for this additional condition will be explained later. Similarly, Protocol II is defined by a two-phase relaying scheme, as shown in Fig. 6, where Phases I and II are repeated alternately. In Phase I, $\mathcal{S}_1$ and $\mathcal{S}_2$ transmit while R_A and $\mathcal{R}_B$ receive. In Phase II, $\mathcal{R}_A$ and $\mathcal{R}_B$ transmit while $\mathcal{D}_1$ and $\mathcal{D}_2$ receive. Note that $\mathcal{D}_1$ and $\mathcal{D}_2$ are inactive in Phase I while $\mathcal{S}_1$ and $\mathcal{S}_2$ are inactive in Phase II.

The detailed procedures at Phases I and II are as follows.

1) Phase I: Since the transmitted signals at $\mathcal{S}_2$ should not disturb that $\mathcal{R}_A$ reliably decodes the received signals from $\mathcal{S}_1$, it is required to satisfy

$$C_1 = \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1}\right) \le \frac{1}{2}C\left(\frac{g_{1A}P_1}{N_A + g_{2A}P_2}\right). \tag{38}$$

To decode the secondary data at $\mathcal{R}_B$, we consider the channel $(\mathcal{S}_1, \mathcal{S}_2)$ to $\mathcal{R}_B$ as a MAC. Since we only consider the case of $C_1 \le (1/2)C(g_{1B}P_1/N_B)$, C_1 is always located inside the MAC capacity region, as shown in Fig. 3, i.e.,

$$2C_1 \le I(X_1; Y_B|X_2) = C\left(\frac{g_{1B}P_1}{N_B}\right) \tag{39}$$

$$2R_2 \le I(X_2; Y_B|X_1) = C\left(\frac{g_{2B}P_2}{N_B}\right) \tag{40}$$

$$2(C_1+R_2) \le I(X_1, X_2; Y_B) = C\left(\frac{g_{1B}P_1+g_{2B}P_2}{N_B}\right). \tag{41}$$

Hence, $\mathcal{R}_B$ can reliably decode the received signals from both $\mathcal{S}_1$ and $\mathcal{S}_2$ if

$$R_2 \le \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{1B}P_1+g_{2B}P_2}{N_B}\right) - 2C_1\right\}. \tag{42}$$

2) Phase II: Since we assume that C_1 is located inside the MAC capacity region in Phase I, the received signals from both $\mathcal{S}_1$ and $\mathcal{S}_2$ are successfully decoded at $\mathcal{R}_B$. This makes it possible for $\mathcal{R}_B$ to know which signal would be transmitted from $\mathcal{R}_A$ to $\mathcal{D}_2$. Hence, $\mathcal{R}_B$ can employ the DPC for the intended receiver $\mathcal{D}_2$ regarding the primary data signals as noncausally known interference [35]. If $\mathcal{R}_B$ transmits the primary data with power of αP_B together with the secondary data with the power of $(1-\alpha)P_B$ after superimposing them as a form of a superposition code such as

$$\underline{x}_B = \sqrt{\frac{\alpha P_B}{P_A}}\underline{x}_A + \sqrt{(1-\alpha)P_B}\underline{x}'_B \tag{43}$$

then the received signals at $\mathcal{D}_1$ are given by

$$\underline{y}_1 = h_{A1}\underline{x}_A + h_{B1}\underline{x}_B + \underline{z}_1 = \left(h_{A1} + h_{B1}\sqrt{\frac{\alpha P_B}{P_A}}\right)\underline{x}_A + h_{B1}\sqrt{(1-\alpha)P_B}\underline{x}'_B + \underline{z}_1 \tag{44}$$

where $\alpha \in [0, 1]$. Hence, $\mathcal{D}_1$ can reliably decode $\underline{x}_A$ if

$$C_1 = \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1}\right) \le \frac{1}{2}C\left(\frac{g_{A1}P_A + g_{B1}\alpha P_B}{N_1 + g_{B1}(1-\alpha)P_B}\right). \tag{45}$$

Note that if C_1 is located outside the MAC capacity region in Phase I, i.e., $C_1 > (1/2)C(g_{1B}P_1/N_B)$, then $\mathcal{R}_B$ cannot decode the received signals from $\mathcal{S}_1$, and α is set to zero. $\alpha = 0$ cannot, however, satisfy (45). Therefore, we propose Protocol II only when $C_1 \le (1/2)C(g_{1B}P_1/N_B)$. On the other hand, since $\mathcal{R}_B$ applies the DPC regarding $\underline{x}_A$ as a noncausally known interference for the intended receiver $\mathcal{D}_2$, and the received signals at $\mathcal{D}_2$ are given by

$$\underline{y}_2 = h_{A2}\underline{x}_A + h_{B2}\underline{x}_B + \underline{z}_2 = \left(h_{A2} + h_{B2}\sqrt{\frac{\alpha P_B}{P_A}}\right)\underline{x}_A + h_{B2}\sqrt{(1-\alpha)P_B}\underline{x}'_B + \underline{z}_2. \tag{46}$$

$\mathcal{D}_2$ can reliably decode the secondary data from $\underline{y}_2$ if

$$R_2 \le \frac{1}{2}C\left(\frac{g_{B2}(1-\alpha)P_B}{N_2}\right) \tag{47}$$

where the effect of the interference $\underline{x}_A$ is completely removed by the DPC [35].

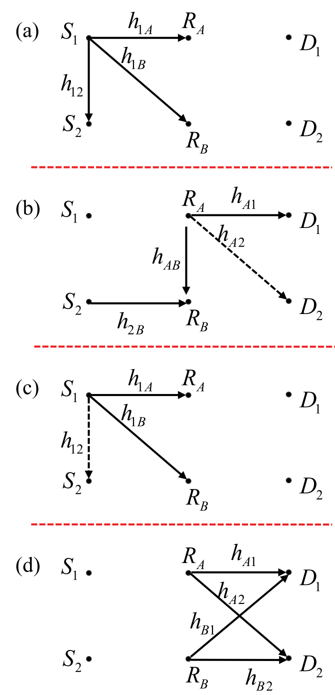

Fig. 7. Protocol III. (a) Phase I. (b) Phase II. (c) Phase III. (d) Phase IV.

Finally, we have the following theorem about the achievable rate of the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ provided by Protocol II.

Theorem 3: If the primary channel is given by the Gaussian two-hop half-duplex relay channel satisfying $g_{1A}P_1/N_A > g_{A1}P_A/N_1$ and $C_1 \le (1/2)C(g_{1B}P_1/N_B)$, then Protocol II provides an achievable rate for the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ given by

$$C_2^- = \frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2^*}{N_B}\right), C\left(\frac{g_{2B}P_2^* + g_{1B}P_1}{N_B}\right) - 2C_1\right. \left. C\left(\frac{g_{B2}(1-\alpha^*)P_B}{N_2}\right)\right\} \tag{48}$$

where

$$P_2^* = \min\left\{\frac{1}{g_{2A}}\left(\frac{g_{1A}P_1}{g_{A1}P_A}\cdot N_1 - N_A\right), P_2\right\} \tag{49}$$

and

$$\alpha^* = \frac{g_{A1}P_A}{N_1 + g_{A1}P_A}. \tag{50}$$

Proof: Equation (48) comes from (42) and (47). Equation (49) is chosen to maximize the RHS of (42) subject to (38). Equation (50) is chosen to maximize the RHS of (47) subject to (45). ■

C. Protocol III

For the case of $g_{1A}P_1/N_A \le g_{A1}P_A/N_1$, we propose Protocol III, which is defined by a four-phase relaying scheme, as shown in Fig. 7, where Phases I, II, III, and IV are repeated sequentially. We notify that $\mathcal{S}_2$ delivers one secondary codeword to $\mathcal{D}_2$ through four channel uses in Protocol III, whereas $\mathcal{S}_2$ does the same through two channel uses in Protocols I and II. In Phases I and III, $\mathcal{S}_1$ transmits while $\mathcal{S}_2$, R_A, and $\mathcal{R}_B$

receive.[5] In Phase II, $\mathcal{S}_2$ and $\mathcal{R}_A$ transmit while $\mathcal{R}_B$ receives. In Phase IV, $\mathcal{R}_A$ and $\mathcal{R}_B$ transmit while $\mathcal{D}_1$ and $\mathcal{D}_2$ receive. In Protocol III, $\mathcal{R}_B$ obtains the secondary data by decoding the received signals from $\mathcal{S}_2$ in Phase II and retransmits them to $\mathcal{D}_2$ in Phase IV. When $\mathcal{R}_B$ obtains the secondary data and retransmits them, its receiving and transmitting schemes can be different depending on whether $\mathcal{S}_2$ and $\mathcal{R}_B$ know which signals would be transmitted at $\mathcal{R}_A$ in Phases II and IV. Therefore, we propose three different schemes according to whether $\mathcal{S}_2$ and $\mathcal{R}_B$ can obtain the primary data by decoding the received signals from $\mathcal{S}_1$ in Phases I and III.

1) Case for $g_{1B}/N_B \geq g_{1A}/N_A$: Since the primary data rate C_1 is less than or equal to the channel capacity of the channel from $\mathcal{S}_1$ to $\mathcal{R}_B$, i.e., $C_1 = (1/2)C(g_{1A}P_1/N_A) \leq (1/2)C(g_{1B}P_1/N_B)$, $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_1$ in Phases I and III. This makes it possible for $\mathcal{R}_B$ to know which signals would be transmitted at $\mathcal{R}_A$ in Phases II and IV. Hence, $\mathcal{R}_B$ subtracts the transmitted signals at $\mathcal{R}_A$ from the received signals in Phase II such that

$$\underline{y}_B - h_{AB}\underline{x}_A = h_{2B}\underline{x}_2 + \underline{z}_B \tag{51}$$

from which $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_2$ if[6]

$$R_2 \leq \frac{1}{4}C\left(\frac{g_{2B}P_2}{N_B}\right). \tag{52}$$

Moreover, $\mathcal{R}_B$ can employ the DPC for the intended receiver $\mathcal{D}_2$ regarding the primary data signals as noncausally known interference in Phase IV [35]. Note that employing the DPC at $\mathcal{R}_B$ in Phase IV is the same as that in Phase II of Protocol II. If $\mathcal{R}_B$ transmits the primary data with power of αP_B together with the secondary data with power of $(1-\alpha)P_B$ after superimposing them as a form of a superposition code such as $\underline{x}_B$ in (43), then the received signals at $\mathcal{D}_1$ in Phase IV are given by $\underline{y}_1$ in (44). Hence, $\mathcal{D}_1$ can reliably decode $\underline{x}_A$ if (45) is satisfied. Since $\mathcal{R}_B$ applies the DPC regarding $\underline{x}_A$ as a noncausally known interference for the intended receiver $\mathcal{D}_2$, and the received signals at $\mathcal{D}_2$ in Phase IV are given by $\underline{y}_2$ in (46), $\mathcal{D}_2$ can reliably decode the secondary data from $\underline{y}_2$ if

$$R_2 \leq \frac{1}{4}C\left(\frac{g_{B2}(1-\alpha)P_B}{N_2}\right). \tag{53}$$

2) Case for $g_{1B}/N_B < g_{1A}/N_A \leq g_{12}/N_S$: Although $\mathcal{R}_B$ cannot decode the received signals from $\mathcal{S}_1$ in Phases I and III, $\mathcal{S}_2$ can reliably decode the received signals from $\mathcal{S}_1$ in Phases I since the primary data rate C_1 is less than or equal to the channel capacity of the channel from $\mathcal{S}_1$ to $\mathcal{S}_2$, i.e., $C_1 = (1/2)C(g_{1A}P_1/N_A) \leq (1/2)C(g_{12}P_1/N_2)$. Hence, $\mathcal{S}_2$ can employ the DPC for the intended receiver $\mathcal{R}_B$ regarding the received signals from $\mathcal{R}_A$ as noncausally known interference in Phase II. Note that employing the DPC at $\mathcal{S}_2$ in Phase II is the same as that in Phase II of the case of $g_{12}/N_S \geq g_{1A}/N_A$ in Protocol I. Then, $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_2$ in Phase II if

$$R_2 \leq \frac{1}{4}C\left(\frac{g_{2B}P_2}{N_B}\right). \tag{54}$$

After obtaining the secondary data in Phase II, $\mathcal{R}_B$ retransmits them to $\mathcal{D}_2$ in Phase IV. Since $\mathcal{R}_B$ cannot reliably decode the received signals from $\mathcal{S}_1$ in Phase III, $\mathcal{R}_B$ transmits only the secondary data in Phase IV. To avoid affecting the fact that $\mathcal{D}_1$ reliably decodes the received signals from $\mathcal{R}_A$ in Phase IV, it is required to satisfy

$$C_1 = \frac{1}{2}C\left(\frac{g_{1A}P_1}{N_A}\right) \leq \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1 + g_{B1}P_B}\right) \tag{55}$$

where the received signals from R_B are simply considered as interference at $\mathcal{R}_A$. To decode the secondary data at $\mathcal{D}_2$ in Phase IV, we consider the channel $(\mathcal{R}_A, \mathcal{R}_B)$ to $\mathcal{D}_2$ as a MAC. If $C_1 \leq (1/2)C(g_{A2}P_A/N_2)$, then C_1 is located inside the MAC capacity region, as shown in Fig. 3, i.e.,

$$2C_1 \leq I(X_A; Y_2|X_B) = C\left(\frac{g_{A2}P_A}{N_2}\right) \tag{56}$$

$$4R_2 \leq I(X_B; Y_2|X_A) = C\left(\frac{g_{B2}P_B}{N_2}\right) \tag{57}$$

$$2C_1 + 4R_2 \leq I(X_A, X_B; Y_2) = C\left(\frac{g_{A2}P_A + g_{B2}P_B}{N_2}\right). \tag{58}$$

Hence, $\mathcal{D}_2$ can reliably decode the received signals from both $\mathcal{R}_A$ and $\mathcal{R}_B$ in Phase IV if

$$R_2 \leq \frac{1}{4}\min\left\{C\left(\frac{g_{B2}P_B}{N_2}\right), C\left(\frac{g_{A2}P_A + g_{B2}P_B}{N_2}\right) - 2C_1\right\}. \tag{59}$$

On the other hand, if $C_1 > (1/2)C(g_{A2}P_A/N_2)$, then $\mathcal{D}_2$ cannot decode the received signals from $\mathcal{R}_A$ in Phase IV. Hence, $\mathcal{D}_2$ can reliably decode the received signals from $\mathcal{R}_B$ in Phase IV if

$$R_2 \leq \frac{1}{4}C\left(\frac{g_{B2}P_B}{N_2 + g_{A2}P_A}\right). \tag{60}$$

3) Case for $g_{1B}/N_B < g_{1A}/N_A$ and $g_{12}/N_S < g_{1A}/N_A$: Since both $\mathcal{S}_2$ and $\mathcal{R}_B$ cannot reliably decode the received signals from $\mathcal{S}_1$ in Phases I and III, the DPC cannot be applied at both of them. Instead, we consider two MACs such as the channel $(\mathcal{R}_A, \mathcal{S}_2)$ to $\mathcal{R}_B$ in Phase II and the channel $(\mathcal{R}_A, \mathcal{R}_B)$ to $\mathcal{D}_2$ in Phase IV. At first, note that considering the channel $(\mathcal{R}_A, \mathcal{S}_2)$ to $\mathcal{R}_B$ in Phase II as a MAC is the same as that in Phase II of the case of $g_{12}/N_S < g_{1A}/N_A$ in Protocol I. If $C_1 \leq (1/2)C(g_{AB}P_A/N_B)$, then C_1 is located inside the MAC capacity region, as shown in Fig. 3, i.e.,

$$2C_1 \leq I(X_A; Y_B|X_2) = C\left(\frac{g_{AB}P_A}{N_B}\right) \tag{61}$$

$$4R_2 \leq I(X_2; Y_B|X_A) = C\left(\frac{g_{2B}P_2}{N_B}\right) \tag{62}$$

$$2C_1 + 4R_2 \leq I(X_A, X_2; Y_B) = C\left(\frac{g_{AB}P_A + g_{2B}P_2}{N_B}\right). \tag{63}$$

[5]Although $\mathcal{S}_2$ receives the signals from $\mathcal{S}_1$ in Phase III, $\mathcal{S}_2$ actually does not decode them, even if $\mathcal{S}_2$ can. $\mathcal{S}_2$ tries to decode the received signals from $\mathcal{S}_1$ only in Phase I.

[6]Since one secondary codeword is delivered from $\mathcal{S}_2$ to $\mathcal{D}_2$ through four channel uses and R_2 is quantified in bits/channel use, $4R_2 \leq C(g_{2B}P_2/N_B)$.

Hence, $\mathcal{R}_B$ can reliably decode the received signals from both $\mathcal{S}_2$ and $\mathcal{R}_A$ in Phase II if

$$R_2 \leq \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{2B}P_2 + g_{AB}P_A}{N_B}\right) - 2C_1 \right\}. \tag{64}$$

On the other hand, if $C_1 > (1/2)C(g_{AB}P_A/N_B)$, then $\mathcal{R}_B$ cannot decode the received signals from $\mathcal{R}_A$. Hence, $\mathcal{R}_B$ can reliably decode the received signals from $\mathcal{S}_2$ in Phase II if

$$R_2 \leq \frac{1}{4} C\left(\frac{g_{2B}P_2}{N_B + g_{AB}P_A}\right). \tag{65}$$

After obtaining the secondary data in Phase II, $\mathcal{R}_B$ retransmits them to $\mathcal{D}_2$ in Phase IV. We consider the channel ($\mathcal{R}_A$, $\mathcal{R}_B$) to $\mathcal{D}_2$ in Phase IV as a MAC, and this is the same as that in Phase IV of the case of $g_{1B}/N_B < g_{1A}/N_A \leq g_{12}/N_S$ in Protocol III. Hence, there is the condition (55) to be satisfied. To obtain the secondary data at $\mathcal{D}_2$ in Phase IV, R_2 is upper bounded by (59) if $C_1 > (1/2)C(g_{A2}P_A/N_2)$ and by (60) otherwise.

Finally, we have the following theorem about the achievable rate of the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ provided by Protocol III.

Theorem 4: If the primary channel is given by the Gaussian two-hop half-duplex relay channel satisfying $g_{1A}P_1/N_A < g_{A1}P_A/N_1$, then Protocol III provides the following achievable rates for the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$.

- If $g_{1B}/N_B \geq g_{1A}/N_A$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}(1-\alpha^*)P_B}{N_2}\right) \right\} \tag{66}$$

where

$$\alpha^* = \frac{g_{A1}P_A}{N_1 + g_{A1}P_A}. \tag{67}$$

- If $g_{1B}/N_B < g_{1A}/N_A \leq g_{12}/N_S$ and $C_1 \leq (1/2)$ $C(g_{A2}P_A/N_2)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right) \right. \\ \left. C\left(\frac{g_{A2}P_A + g_{B2}P_B^*}{N_2}\right) - 2C_1 \right\} \tag{68}$$

where

$$P_B^* = \min \left\{ \frac{1}{g_{B1}} \left(\frac{g_{A1}P_A}{g_{1A}P_1} \cdot N_A - N_1\right), P_B \right\}. \tag{69}$$

- If $g_{1B}/N_B < g_{1A}/N_A \leq g_{12}/N_S$ and $C_1 > (1/2)$ $C(g_{A2}P_A/N_2)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2 + g_{A2}P_A}\right) \right\}. \tag{70}$$

- If $g_{1B}/N_B < g_{1A}/N_A, g_{12}/N_S < g_{1A}/N_A, C_1 \leq (1/2)$ $C(g_{AB}P_A/N_B)$, and $C_1 \leq (1/2)C(g_{A2}P_A/N_2)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{AB}P_A + g_{2B}P_2}{N_B}\right) - 2C_1 \right. \\ \left. C\left(\frac{g_{B2}P_B^*}{N_2}\right), C\left(\frac{g_{A2}P_A + g_{B2}P_B^*}{N_2}\right) - 2C_1 \right\}. \tag{71}$$

- If $g_{1B}/N_B < g_{1A}/N_A$, $g_{12}/N_S < g_{1A}/N_A$, and $(1/2)$ $C(g_{A2}P_A/N_2) < C_1 \leq (1/2)C(g_{AB}P_A/N_B)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{AB}P_A + g_{2B}P_2}{N_B}\right) - 2C_1 \right. \\ \left. C\left(\frac{g_{B2}P_B^*}{N_2 + g_{A2}P_A}\right) \right\}. \tag{72}$$

- If $g_{1B}/N_B < g_{1A}/N_A$, $g_{12}/N_S < g_{1A}/N_A$, and $(1/2)$ $C(g_{AB}P_A/N_B) < C_1 \leq (1/2)C(g_{A2}P_A/N_2)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B + g_{AB}P_A}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right) \right. \\ \left. C\left(\frac{g_{A2}P_A + g_{B2}P_B^*}{N_2}\right) - 2C_1 \right\}. \tag{73}$$

- If $g_{1B}/N_B < g_{1A}/N_A, g_{12}/N_S < g_{1A}/N_A, C_1 > (1/2)$ $C(g_{AB}P_A/N_B)$, and $C_1 > (1/2)C(g_{A2}P_A/N_2)$, then

$$C_2^- = \frac{1}{4} \min \left\{ C\left(\frac{g_{2B}P_2}{N_B + g_{AB}P_A}\right), C\left(\frac{g_{B2}P_B^*}{N_2 + g_{A2}P_A}\right) \right\}. \tag{74}$$

Proof: Equation (66) comes from (52) and (53). Equation (67) is chosen to maximize the RHS of (53) subject to (45). Equation (68) comes from (54) and (59). Equation (69) is chosen to maximize the RHS of (59) and (60) subject to (55). Equation (70) comes from (54) and (60). Equation (71) comes from (59) and (64). Equation (72) comes from (60) and (64). Equation (73) comes from (59) and (65). Equation (74) comes from (60) and (65). ■

In Table I, we summarize the achievable rates of the secondary pair $(\mathcal{S}_2, \mathcal{D}_2)$ provided by Protocols I, II, and III. Note that either Protocol I or II can be used if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$ and $g_{1B}P_1/N_B \geq g_{A1}P_A/N_1$, but only one of Protocols I, II, and III can be used otherwise.

Since Protocol III operates in four phases while Protocols I and II operate in two phases, Protocol III is most complex. Nevertheless, Protocol III is the only protocol that can be used when $g_{1A}P_1/N_A \leq g_{A1}P_A/N_1$. Although Protocols I and II have similar complexity, they utilize quite different channel paths such that the performance of Protocol I is proportional to g_{12}, g_{AB}, and $1/g_{BA}$, regardless of g_{1B} and g_{2A}, whereas the performance of Protocol II is proportional to g_{1B} and $1/g_{2A}$ regardless of g_{12}, g_{AB}, and g_{BA}.

TABLE I
ACHIEVABLE RATES OF THE SECONDARY PAIR $(\mathcal{S}_2, \mathcal{D}_2)$ PROVIDED BY PROTOCOLS I, II, AND III

Protocol	Condition			C_2^-
I	$\frac{g_{1A}P_1}{N_A} > \frac{g_{A1}P_A}{N_1}$, $C_1 = \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1}\right)$, P_B^* in (35)	$\frac{g_{12}}{N_S} \geq \frac{g_{1A}}{N_A}$		$\frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\}$
		$\frac{g_{12}}{N_S} < \frac{g_{1A}}{N_A}$	$C_1 \leq \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$	$\frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{2B}P_2+g_{AB}P_A}{N_B}\right) - 2C_1, C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\}$
			$C_1 > \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$	$\frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2}{N_B+g_{AB}P_A}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right)\right\}$
II	$\frac{g_{1A}P_1}{N_A} > \frac{g_{A1}P_A}{N_1}$, $C_1 = \frac{1}{2}C\left(\frac{g_{A1}P_A}{N_1}\right) \leq \frac{1}{2}C\left(\frac{g_{1B}P_1}{N_B}\right)$, P_2^* in (49), α^* in (50)			$\frac{1}{2}\min\left\{C\left(\frac{g_{2B}P_2^*}{N_B}\right), C\left(\frac{g_{2B}P_2^*+g_{1B}P_1}{N_B}\right) - 2C_1, C\left(\frac{g_{B2}(1-\alpha^*)P_B}{N_2}\right)\right\}$
III	$\frac{g_{1A}P_1}{N_A} \leq \frac{g_{A1}P_A}{N_1}$, $C_1 = \frac{1}{2}C\left(\frac{g_{1A}P_1}{N_A}\right)$	$\frac{g_{1B}}{N_B} \geq \frac{g_{1A}}{N_A}$, α^* in (67)		$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}(1-\alpha^*)P_B}{N_2}\right)\right\}$
		$\frac{g_{1B}}{N_B} < \frac{g_{1A}}{N_A}$, $\frac{g_{12}}{N_S} \geq \frac{g_{1A}}{N_A}$, P_B^* in (69)	$C_1 \leq \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right), C\left(\frac{g_{A2}P_A+g_{B2}P_B^*}{N_2}\right) - 2C_1\right\}$
			$C_1 > \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{B2}P_B^*}{N_2+g_{A2}P_A}\right)\right\}$
		$\frac{g_{1B}}{N_B} < \frac{g_{1A}}{N_A}$, $\frac{g_{12}}{N_S} < \frac{g_{1A}}{N_A}$, P_B^* in (69)	$C_1 \leq \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$, $C_1 \leq \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{AB}P_A+g_{2B}P_2}{N_B}\right) - 2C_1, C\left(\frac{g_{B2}P_B^*}{N_2}\right), C\left(\frac{g_{A2}P_A+g_{B2}P_B^*}{N_2}\right) - 2C_1\right\}$
			$C_1 \leq \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$, $C_1 > \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B}\right), C\left(\frac{g_{AB}P_A+g_{2B}P_2}{N_B}\right) - 2C_1, C\left(\frac{g_{B2}P_B^*}{N_2+g_{A2}P_A}\right)\right\}$
			$C_1 > \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$, $C_1 \leq \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B+g_{AB}P_A}\right), C\left(\frac{g_{B2}P_B^*}{N_2}\right), C\left(\frac{g_{A2}P_A+g_{B2}P_B^*}{N_2}\right) - 2C_1\right\}$
			$C_1 > \frac{1}{2}C\left(\frac{g_{AB}P_A}{N_B}\right)$, $C_1 > \frac{1}{2}C\left(\frac{g_{A2}P_A}{N_2}\right)$	$\frac{1}{4}\min\left\{C\left(\frac{g_{2B}P_2}{N_B+g_{AB}P_A}\right), \left(\frac{g_{B2}P_B^*}{N_2+g_{A2}P_A}\right)\right\}$

IV. NUMERICAL RESULTS

Here, the performance of the proposed two-hop relaying protocols is examined through computer simulations. We first consider the full-duplex two-hop relaying CR communications with a single shared relay in Section II. The simulation environments are as follows. The average transmission rates of $\mathcal{S}_1$ and $\mathcal{S}_2$, which are denoted by $\bar{C}_1$ and $\bar{C}_2^-$, respectively, are obtained based on 10^6 realizations of the channel gains g_{1R}, g_{R1}, g_{2R}, and g_{R2}, which are independent of each other, and each of them follows a Rayleigh distribution. The average channel gains and noise powers are fixed at one, i.e., $\mathbb{E}[g_{11}] = \mathbb{E}[g_{22}] = \mathbb{E}[g_{12}] = \mathbb{E}[g_{21}] = 1$ and $N_1 = N_2 = 1$. The transmission powers P_1, P_2, and P_R are varied, so that the SNR P_i/N_i for $i \in \{1, 2, R\}$ can take between 0 and 20 dB. For simplicity, it is assumed that the SNRs are identical, i.e., $P_1/N_1 = P_2/N_2 = P_R/N_R$. We notify that the secondary sender stops working occasionally whenever $g_{1R}P_1/N_R > g_{R1}P_R/N_1$ by the condition in Lemma 1.

The average primary channel capacity $\bar{C}_1$ and the average secondary achievable rate $\bar{C}_2^-$ are shown in Fig. 8, where we can see that $\bar{C}_2^-$ has nonzero values for all SNR values. These results are somewhat surprising, although $\bar{C}_2^-$ is relatively small compare with $\bar{C}_1$, because $\bar{C}_2^-$ is obtained even when the primary sender and receiver have no prior knowledge about the secondary sender and receiver, and moreover, there is no loss at the primary channel capacity. It is also found that $\bar{C}_2$ increases as the SNR increases, but its rate of increase seems to be decreased as the SNR increases. This is because $C_2^- = \min\{C(g_{2R}P_2/(N_R + g_{1R}P_1)), C((g_{R2}(1-\alpha^*)P_R)/N_2)\}$ in (11) converges to $C(g_{2R}P_2/g_{1R}P_1)$ as the SNR increases.

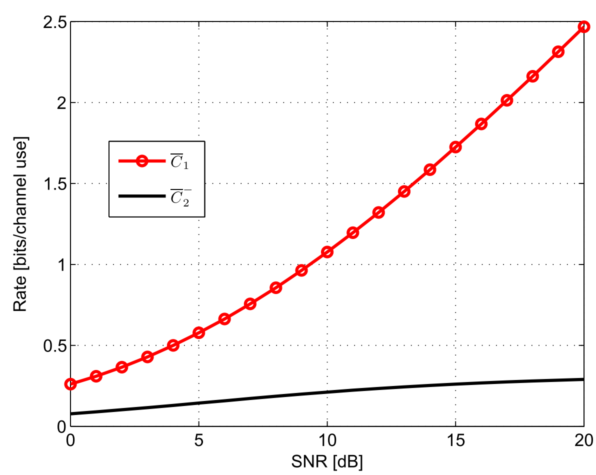

Fig. 8. $\bar{C}_1$ and $\bar{C}_2^-$ for a Gaussian two-hop relay channel with one relay.

We next consider two-hop half-duplex relaying CR communications with one primary relay and one secondary relay in Section III. Similarly, the average transmission rates of $\mathcal{S}_1$ and $\mathcal{S}_2$ are obtained based on 10^6 realizations of the channel gains, which are independent of each other, and each of them follows a Rayleigh distribution. Fixing the noise powers at one, i.e., $N_1 = N_2 = N_A = N_B = 1$, the transmission powers P_1, P_2, P_A, and P_B are varied so that SNR P_i/N_i for $i \in \{1, 2, A, B\}$ can take between 0 and 20 dB, where we assume $P_1/N_1 = P_2/N_2 = P_A/N_A = P_B/N_B$ for simplicity. Note that Protocol I can be applied if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, and Protocol III can be applied otherwise, whereas Protocol II

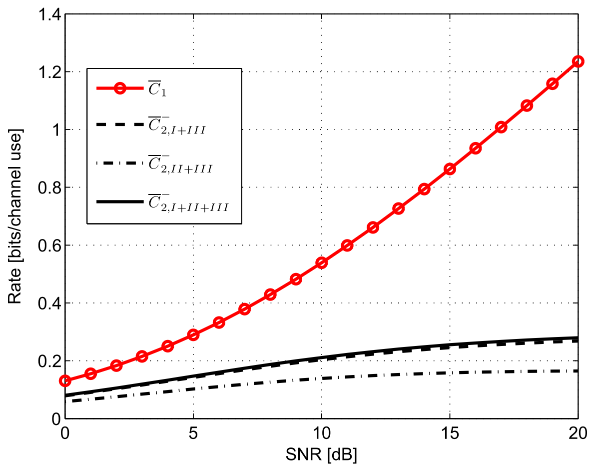

Fig. 9. $\bar{C}_1$, $\bar{C}^-_{2,\mathrm{I+II}}$, and $\bar{C}^-_{2,\mathrm{I+III}}$ for a Gaussian two-hop half-duplex relay channel with one primary relay and one secondary relay when all the average channel gains are fixed at one.

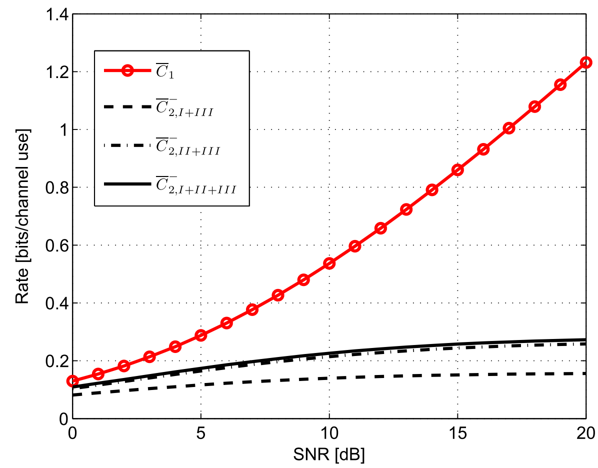

Fig. 10. $\bar{C}_1$, $\bar{C}^-_{2,\mathrm{I+II}}$, and $\bar{C}^-_{2,\mathrm{I+III}}$ for a Gaussian two-hop half-duplex relay channel with one primary relay and one secondary relay when all the average channel gains are fixed at one but $\mathbb{E}[g_{AB}] = \mathbb{E}[g_{BA}] = \mathbb{E}[g_{1B}] = 10$ and $\mathbb{E}[g_{12}] = 0.1$.

can be applied if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$ and $g_{A1}P_A/N_1 \leq g_{1B}P_1/N_B$. Hence, to evaluate the average secondary achievable rate, we consider three possible combinations of the proposed protocols as follows.

- Protocol I operates if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$, and Protocol III operates otherwise. The corresponding average achievable rate is denoted by $\bar{C}^-_{2,\mathrm{I+III}}$.
- Protocol II operates if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$ and $g_{A1}P_A/N_1 \leq g_{1B}P_1/N_B$, whereas Protocol III operates if $g_{1A}P_1/N_A \leq g_{A1}P_A/N_1$. Note that this combination does not work if $g_{1A}P_1/N_A > g_{A1}P_A/N_1 > g_{1B}P_1/N_B$. The corresponding average achievable rate is denoted by $\bar{C}^-_{2,\mathrm{II+III}}$.
- Protocol II operates if $g_{1A}P_1/N_A > g_{A1}P_A/N_1 > g_{1B}P_1/N_B$, and Protocol III operates if $g_{1A}P_1/N_A \leq g_{A1}P_A/N_1$. The best between Protocols I and II operates if $g_{1A}P_1/N_A > g_{A1}P_A/N_1$ and $g_{A1}P_A/N_1 \leq g_{1B}P_1/N_B$. The corresponding average achievable rate is denoted by $\bar{C}^-_{2,\mathrm{I+II+III}}$.

Note that except for the combination of Protocols II and III, the other two combinations of the proposed two-hop relaying protocols make it *always* possible for the secondary sender to transmit data regardless of the channel conditions.

The average secondary achievable rates $\bar{C}^-_{2,\mathrm{I+III}}$, $\bar{C}^-_{2,\mathrm{II+III}}$, and $\bar{C}^-_{2,\mathrm{I+II+III}}$ are shown in Fig. 9 when all the average channel gains are fixed at one, i.e., $\mathbb{E}[g_{1A}] = \mathbb{E}[g_{1B}] = \cdots = \mathbb{E}[g_{12}] = 1$. In Fig. 9, we can see that the combination of Protocols I and III is better than the combination of Protocols II and III, i.e., $\bar{C}^-_{2,\mathrm{I+III}} > \bar{C}^-_{2,\mathrm{II+III}}$ because when $g_{1A}P_1/N_A > g_{A1}P_A/N_1 > g_{1B}P_1/N_B$, the combination of Protocols II and III stops working occasionally. On the other hand, when all the average channel gains are fixed at one but $\mathbb{E}[g_{AB}] = \mathbb{E}[g_{BA}] = \mathbb{E}[g_{1B}] = 10$ and $\mathbb{E}[g_{12}] = 0.1$, the combination of Protocols I and III is worse than the combination of Protocols II and III, i.e., $\bar{C}^-_{2,\mathrm{I+III}} < \bar{C}^-_{2,\mathrm{II+III}}$, as shown in Fig. 10. In this case, $\mathbb{E}[g_{1B}]$ is relatively large, and hence, it is less probable for the combination of Protocols II and III to stop working by the condition $g_{1A}P_1/N_A > g_{A1}P_A/N_1 > g_{1B}P_1/N_B$. Moreover, as g_{12} becomes smaller, Protocol I has fewer chances to exploit the DPC at the secondary sender, and the rate loss caused by not exploiting the DPC becomes more significant as g_{AB} and g_{BA} become larger, whereas Protocol II operates regardless of g_{12}, g_{AB}, and g_{BA}. As expected, $\bar{C}^-_{2,\mathrm{I+II+III}}$ has the best performance among the three possible combinations in both Figs. 9 and 10. We can also see that all of $\bar{C}^-_{2,\mathrm{I+III}}$, $\bar{C}^-_{2,\mathrm{II+III}}$, and $\bar{C}^-_{2,\mathrm{I+II+III}}$ have nonzero values for all SNR values.

V. Conclusion

We have proposed two-hop relaying protocols for CR communications that allow the secondary sender to access the spectrum bands that are used by the primary user and still cause no loss at the primary channel capacity. We considered both full-duplex and half-duplex relays. To make it possible, we exploited a unique property of the primary channel capacity, as well as a unique property of the half-duplex relaying. It was shown through computer simulations that the average achievable rates of the proposed two-hop relaying protocols are nonzero values over a wide range of SNRs. These results are significantly important since they are obtained even when the primary nodes have no prior knowledge about the secondary nodes, and moreover, there is no loss at the average primary channel capacity.

Further work in this area will include the extension of this CR system to support multiple primary/secondary nodes in a scalable fashion. It would be also interesting to see how much the secondary rate can be increased at the expense of interaction with primary nodes if primary nodes are allowed to have some prior knowledge.

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